

Search for 511 keV Emission in Satellite Galaxies of the Milky Way with INTEGRAL/SPI

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ABSTRACT

Context. The positron (e^+) annihilation γ -ray signal in the Milky Way (MW) shows a puzzling morphology: a very bright bulge and a very low surface-brightness disk. A coherent explanation of the e^+ origin, propagation through the Galaxy and subsequent annihilation in the interstellar medium has not yet been found. Tentative explanations involve e^+ s from radioactivity, X-ray binaries, and dark matter (DM).

Aims. Dwarf satellite galaxies (DSGs) are believed to be DM-dominated and hence are promising candidates in the search for 511 keV emission as a result of DM annihilation into e^+e^- -pairs. The goal of this study is to constrain possible 511 keV γ -ray signals from 39 DSGs of the MW and to test the annihilating DM scenario.

Methods. We use the spectrometer SPI on INTEGRAL to extract individual spectra for the studied objects in the range 490–530 keV. As the diffuse galactic 511 keV emission dominates the overall signal, the large scale morphology of the MW has been modelled accordingly and was included in a maximum likelihood analysis. Alternatively, a distance-weighted stacked spectrum has been determined, representing an average DSG seen in 511 keV.

Results. Only Reticulum II (Ret II) shows a 3.1σ signal. Five other sources show tentative 2σ signals. The mass-to-511 keV-luminosity-ratio, Υ_{511} , shows a marginal trend towards higher values for intrinsically brighter objects, opposite to the mass-to-light-ratio, Υ_V in the V-band, which is generally used to uncover DM in DSGs.

Conclusions. All derived 511 keV flux values or upper limits are above the flux level implied by a DM interpretation of the MW bulge signal. The signal detected from Ret II is unlikely to be related to a DM origin alone, otherwise, the MW bulge would be ~ 100 times brighter in 511 keV than what is seen with SPI. Ret II is exceptional considering the DSG sample, and rather points to enhanced recent star formation activity, if its origins are similar to processes in the MW. Understanding this emission may provide further clues regarding the origin of the annihilation emission in the MW bulge.

Key words. Positrons, Gamma rays: general, ISM: general, Galaxies: dwarf satellites, Techniques: spectroscopic, Cosmology: dark matter

1. Introduction

It has been proposed that the 511 keV morphology of the Milky Way (MW), originating in the annihilation of electrons (e^- s) with positrons (e^+ s), seen by INTEGRAL (Winkler et al. 2003), could be related to the decay or annihilation of dark matter (DM) particles (Hooper et al. 2004; Ascasibar et al. 2006). From theoretical considerations it was suggested that when light DM particles ($1 \text{ MeV } c^{-2} \lesssim m_\chi \lesssim 100 \text{ MeV } c^{-2}$) annihilate or decay, they could produce e^+ s with low kinetic energies of $\sim \text{MeV}$ (Boehm et al. 2004; Hooper et al. 2004; Picciotto & Pospelov 2005; Beacom & Yüksel 2006; Gunion et al. 2006; Pospelov et al. 2008; Boehm & Silk 2008). The annihilation of these e^+ s with e^- s from the interstellar medium (ISM) would lead to the signature that was measured by the spectrometer SPI (Vedrenne et al. 2003) on INTEGRAL.

The galactic diffuse large-scale 511 keV emission that was measured with balloon-flight experiments (e.g. Leventhal et al.

1978) and with SPI (Knödlseider et al. 2005; Bouchet et al. 2010; Skinner et al. 2014) was found to be concentrated towards the bulge region of the MW, reminiscent of a DM halo profile. However, other – less exotic – sources may also explain this signal (see Prantzos et al. 2011, for a review).

If the entire bulge annihilation radiation originates from DM particles, the apparently DM-dominated dwarf satellite galaxies (DSGs) of the MW should also emit a measurable 511 keV signal (Hooper et al. 2004; Simon & Geha 2007; Strigari et al. 2008b). Based on cold dark matter (CDM) cosmology and the corresponding galaxy formation model (see e.g. White & Rees 1978; Springel et al. 2005; Moster et al. 2013), the satellite galaxies of the MW must be DM-dominated (Mateo 1998; Strigari et al. 2008a; McConnachie 2012).

A good test of the annihilating DM hypothesis is thus to check in cumulative INTEGRAL data for a consistent 511 keV brightness from the known satellites of the MW, depending on their DM content and distance. Cordier et al. (2004) tested this for the case of the Sagittarius Dwarf Spheroidal (Sag). A point-like emission, as expected from DM annihilation (see below),

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the distribution of annihilating DM in an astrophysical system. Typical dark matter density profiles follow a power law in the inner regions, $\rho(r) \propto r^{-\gamma}$ (Burkert 1995; Navarro et al. 1996; Merritt et al. 2006) with $0 < \gamma \leq 2$. The ρ^2 dependence of the J-factor thus yields a very sharply peaked signal, in most cases. Generally, compilations of dwarf galaxy J-factors in the literature (e.g. Ackermann et al. 2014; Evans et al. 2016) yield regions of interest that are smaller than the imaging resolution of SPI $\sim 2.7^\circ$, so that the point-like assumption is adequate. For example, the imaging resolution of SPI encompasses a physical region of more than 400 pc for the closest DSG in our sample, Canis Major (CMA), at a distance of 9 kpc.

Our input catalogue of all² DSGs near the MW within 500 kpc holds 39 individual candidate sources. We use the baryonic centres of the DSGs as the positions of the point-sources, see Tab. 1. This leads to 39 additional intensity scaling parameters θ_i in the model fit to the observed data. These sources are at least separated by more than the imaging resolution of SPI (2.7°), and thus the correlation between them (source confusion) is usually negligible. Exceptionally "close pairs" (see Fig. 1) are CVn I – CVn II (6.5°), Leo I – Seg 1 (3.8°), Leo IV – Leo V (2.8°), and Boo I – Boo II (1.7°), so that the flux values derived from the latter pair only should be considered with caution.

For each galaxy, an individual spectrum in the range 490–530 keV was extracted. Then, in each spectrum, we determined the flux of annihilation emission separately. Due to the individually low signals, we additionally consider an alternative *stacking* approach for a DM hypothesis test. In this case, instead of deriving 39 individual spectra, we fix their relative fluxes according to their distances, assuming the same mass for all DSGs (Strigari et al. 2008a). This obtains a spectrum for a reference DSG at a chosen distance of $D_0 = 100$ kpc. The resulting spectrum, however, would be dominated by the closest galaxy as the flux is proportional to the inverse distance squared, and may also be confused by the diffuse emission in the galactic plane and bulge, due to their partial correlation in the maximum likelihood approach. We try to avoid such a bias – in the stacking procedure only – by ignoring DSGs towards the galactic plane (between $|b| < 10^\circ$), and galaxies closer than 25 kpc. Formally, the additional (now seventh, see Paper I) sky component is described by Eq. (3)

$$F = \frac{\langle L_0 \rangle}{4\pi D_0^2} \sum_{i=1}^{39} \delta(l - l_i) \delta(b - b_i) \left(\frac{D_0}{D_i} \right)^2. \quad (3)$$

Here $\langle L_0 \rangle$ is the (fitted) intrinsic mean luminosity for a basic DSG at a canonical distance of $D_0 = 100$ kpc, corresponding to 39 individual sources, at positions (l_i/b_i) in the sky, scaled by their distances D_i .

3. Results

3.1. Individual Sources

We first validate the emission attributed to the diffuse large-scale 511 keV emission to obtain a robust reference model with respect to possible additional sources. We find the bright bulge and faint disk, as well as the Galactic Centre Source (GCS), the Crab and Cygnus X-1 with fluxes consistent with the results reported in Paper I. The flux values for bulge, disk and GCS are $(9.5 \pm 0.7) \times 10^{-4}$ ph cm⁻² s⁻¹, $(16.7 \pm 3.6) \times 10^{-4}$ ph cm⁻² s⁻¹, and $(0.8 \pm$

$0.2) \times 10^{-4}$ ph cm⁻² s⁻¹, respectively. Continuum fluxes in the analysed 40 keV band are $(2.20 \pm 0.07) \times 10^{-5}$ ph cm⁻² s⁻¹ keV⁻¹ for the Crab, and $(0.65 \pm 0.05) \times 10^{-5}$ ph cm⁻² s⁻¹ keV⁻¹ for Cygnus X-1, also consistent with literature values (see e.g. Jourdain & Roques 2009; Jourdain et al. 2012).

The derived spectra for each DSG near 511 keV were fitted by a Gaussian-shaped line with width fixed at 2.15 keV (instrumental resolution, FWHM) on top of a constant offset. The centroid was allowed to vary in the range 508–514 keV, corresponding to bulk motions of $|v_{\text{Bulk}}| \approx 1750$ km s⁻¹, to account for intrinsic movement of the satellites and statistical fluctuations. For non-positive results, a 2σ flux limit is estimated, for a line at 511 keV.

The strongest DSG signal that we find is from the position of Reticulum II (Ret II), with 3.1σ significance. Its line flux is $(17.0 \pm 5.4) \times 10^{-5}$ ph cm⁻² s⁻¹. However, we caution that Ret II 511 keV emission may be too intense a signal to be interpreted as due to DM alone (see Discussion below). For the position of Sag, a 511 keV line significance of 2.3σ is found. Formally, the line flux is $(2.2 \pm 1.0) \times 10^{-5}$ ph cm⁻² s⁻¹, consistent with the upper limits derived from Cordier et al. (2004), with a now ~ 100 times larger exposure at this position.

The summary of fit results for all 39 tested satellite positions is listed in Tab. 1 and illustrated in Fig. 2. The exposure across the entire sky in this data set varies by a factor of 50 among the candidate sources, and the sensitivity changes accordingly. We empirically determine a 2σ narrow 511 keV line detection sensitivity of $5.7 \times 10^{-5} \times \sqrt{10^6/T_{\text{Exp}}[\text{Ms}]}$ ph cm⁻² s⁻¹ (solid line in Fig. 2). Among our sample of 39 candidate sources, 17 show weak indications of annihilation signals ($\geq 1\sigma$), independent of the exposure time. Six sources show a signal with more than 2σ (Leo I, Gru I, CVn II, Sag), and two sources more than 3σ (Boo I, Ret II) statistical significance above instrumental background. The values for Boo I may be over-/underestimated due to source confusion with Boo II. Statistically, one would expect about two 2σ sources out of a sample of 39 from fluctuations of the background. Since we see six sources at a significance of at least 2σ (two expected), and 17 sources at a significance of at least 1σ (13 expected), the 511 keV signals are not consistent with background fluctuations only. On the other hand, the individual 511 keV signals per source are of too low significance to single them out, and thus we will use the full population of possible sources for further analyses (see Sec. 4.1). Furthermore, we discuss the 3.1σ signal from Ret II in Sec. 4.3, separately.

3.2. Stacked Analysis

Under the assumption that satellite galaxies share a common mass scale (Strigari et al. 2008a), we analyse the spectra in a constrained maximum likelihood fit to search for a DM-related 511 keV signal. For this, we determine one global scaling parameter to the set of sources, which are normalised to a common flux value and then re-scaled by their distances D^{-2} . We estimate the total γ -ray flux in the vicinity of 511 keV that reaches us from the positions of the Milky Way satellites (see Eq.(3)), and also avoid source confusion as above. In the stacked spectrum of the satellite galaxies at a canonical distance of 100 kpc, we do not find a significant excess and provide a 2σ upper limit of the flux of 1.4×10^{-4} ph cm⁻² s⁻¹. This is based on ignoring DSGs closer than 25 kpc and DSGs in the direction of the galactic disk. Softening these restrictions by including all 39 DSGs changes this upper limit to 1.3×10^{-4} ph cm⁻² s⁻¹. If the assumption of an identical DSG mass is discarded, Eq. (3) gets an additional fac-

² During the write-up of this study, more DSGs have been found but have not been included in the analysis.

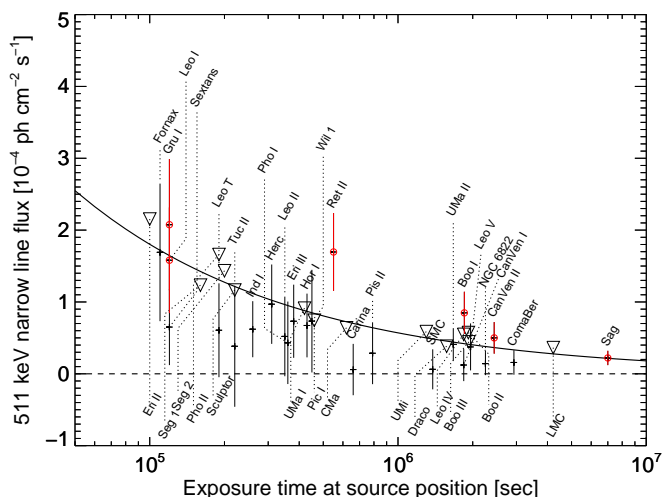


Fig. 2: Derived fluxes (crosses) of each satellite galaxy against the exposure time at source position. If a line is not detected or appears negative, a 2σ upper limit is given (triangle). The solid line represents the 2σ sensitivity limit for a narrow line (instrumental resolution) seen with SPI at 511 keV. The (red) circles indicate sources for which the statistical significance is higher than 2σ .

tor M_i^2 where M_i is the dynamical mass of the DSG. For a subset of galaxies with available J-factor and dynamical mass estimates (see Tab. 1), we derive an upper limit of 2.3×10^{-4} ph cm $^{-2}$ s $^{-1}$. Under the same assumptions, with the requirement that DM annihilation explains the entire bulge signal (Vincent et al. 2012; Evans et al. 2016), the stacked dark matter signal would yield a 511 keV flux of $\sim 2 \times 10^{-6}$ ph cm $^{-2}$ s $^{-1}$.

4. Discussion

4.1. Mass-to-Light-Ratios

The mass-to-light-ratio $\Upsilon_V = M_{\text{Dyn}}/L_V$ has been found to be a good indicator for DM which is believed to dominate the mass content in DSGs (Mateo 1998; Strigari et al. 2008a; McConnachie 2012). In the top-panel of Fig. 3, the mass-to-light ratio within the half-light radius (see references in Tab. 1) against the absolute V-band magnitude from available literature data is shown. For Pis II, Boo III, CMa, and the LMC, no dynamical mass estimate is available and we used the stellar masses as lower limits for the dynamical masses. As already shown by several studies (Mateo 1998; Strigari et al. 2008a; McConnachie 2012), the mass-to-light-ratio shows a negative correlation with the brightness of the objects. This is counter-intuitive as naturally one would expect a nearly constant mass-to-light-ratio in the absence of dark matter, no matter how faint a galaxy is. The stellar-mass-to-light-ratio $\Upsilon_V^* = M^*/L_V$ indeed shows a value of ~ 1.0 across the magnitude scale. But as the galaxies become fainter, Υ_V rises, which indicates an unseen mass, generally interpreted as DM sub-halos. We note that also the ultra-faint dwarf galaxies (data available for Hor I and Ret II), recently detected by Koposov et al. (2015a), nicely fit into this correlation.

Any tracer that would make DM "visible", e.g. by measuring its annihilation products, should show a similar trend. We therefore define a mass-to-positron-annihilation-luminosity-ratio, $\Upsilon_{511} = M_{D_{\text{dyn}}}/L_{511}$, and calculate these values for our sample. In the bottom panel of Fig. 3, we show Υ_{511} for the galaxies

whose flux estimates deviate from zero (at the 1σ level). For all other galaxies for which data are available, we give 2σ lower limits. Apparently, and although the data have large uncertainties, the correlation is opposite to Υ_V . The reversed trend for Υ_{511} versus M_V is in contradiction with what is expected for a DM origin. This could have several causes:

1. The correlation is based on the high ratio derived from Sag; by neglecting this value, the rank correlation coefficient reduces from -0.35 to -0.14 , but is still far from the positive correlation in the top panel. Using only signals with more than 2σ does also yield the same correlation.
2. For the visually fainter galaxies (e.g. Ret II, Hor I) seen in 511 keV, the dynamical mass estimates are 2-3 orders of magnitude lower than for the bright galaxies (e.g. Sag, For) which automatically distorts the correlation in this direction, if the signals are not significant or strong.
3. It is probably not the dynamical mass which drives the apparent correlation: As the correlation of Υ_V^* versus M_V is completely gone, the respective correlation between Υ_{511}^* and M_V is still there. Stars and their surrounding environments are a favoured explanation for any present 511 keV emission (see discussion about Ret II below), though the electron number density in DSGs is a crucial but uncertain factor in theoretical estimations of the annihilation rate.

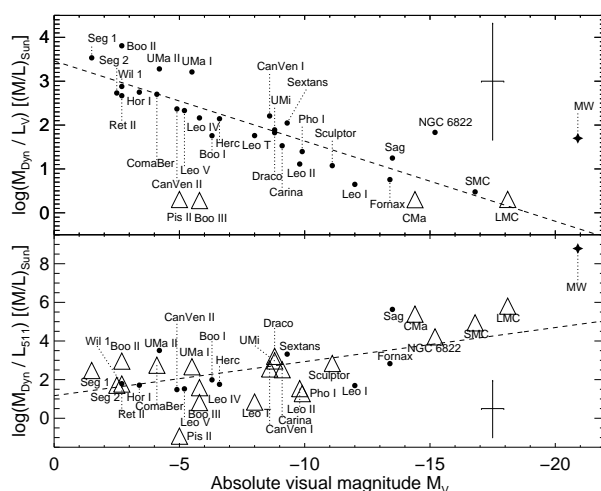


Fig. 3: Mass-to-luminosity ratio in units of solar masses per solar luminosity as a function of absolute visual magnitude, M_V . Top panel shows the dynamical mass over the absolute V-band magnitude as already described by Mateo (1998), Strigari et al. (2008a), or McConnachie (2012). Towards fainter satellite galaxies, Υ_V increases, which is generally interpreted as indirect evidence for dark matter (see text for details). Bottom panel shows the ratio of the dynamical mass and the 511 keV luminosity over absolute visual magnitude. The trend is reversed when plotting Υ_{511} versus M_V , in contradiction with what is expected for a dark matter origin. Typical error bars are shown; 2σ lower limits are shown by triangles. For comparison, Υ_V and Υ_{511} for the Milky Way are shown with a star symbol in each panel.

4.2. Dark Matter Origin

The pronounced spatial peak of the 511 keV signal in the galactic centre has been confirmed and strengthened by recent results

(Paper I), reviving the possibility of a DM origin. If e^+ s do not travel far from the source and rather find free or bound e^- s to annihilate with (Guessoum et al. 1991, 2005; Jean et al. 2009; Alexis et al. 2014), the morphology would match the square of a host galaxy's DM density profile (e.g. Burkert 1995; Navarro et al. 1996; Merritt et al. 2006). Interestingly, the peak of such a profile seen in 511 keV has been determined to be around $(l/b) = (-1.25/-0.25)^\circ$ (Kuhlen et al. 2013; Skinner et al. 2014). Vincent et al. (2012) found that Einasto profiles also fit the data well, assuming a DM halo centred on the galactic centre position. Upper limits on the 1-2 MeV γ -ray continuum (Boehm et al. 2004; Boehm & Silk 2008; Beacom & Yüksel 2006) limit the DM particle mass to $m_{DM} \lesssim 7 \text{ MeV } c^{-2}$. These studies also conclude that the morphology of the signal precludes a decay-induced signal.

In the case of the DSGs, the signal would be seen by SPI as a point-like source, and the 511 keV flux, F_{511} , would follow $F_{511} = \frac{1}{4\pi m_{DM}^2} \langle \sigma v \rangle J$, assuming negligible positronium formation in the dwarfs, where $\langle \sigma v \rangle$ is the thermally averaged cross section, m_{DM} is the DM particle mass, and J the J-factor, see Eq. (2). Hooper et al. (2004) estimated that if the whole 511 keV emission in the bulge of the MW was due to the annihilation of light DM particles into e^-e^+ -pairs, an observable 511 keV emission from the direction of Sag would be about 3-6 times smaller than in the MW bulge. In our analysis, this ratio is 42 ± 19 , ruling out this hypothesis by $\sim 2\sigma$, though it is worth pointing out that the flux ratio between the GCS and Sag is 3.5 ± 2.1 . If the Sag signal is entirely due to DM, this would indicate a DM contribution to the galactic signal of $\sim 3\%$. However, more recent fits to the bulge emission require a DM annihilation cross section that is a factor of 5 (Ascasibar et al. 2006) to 10 (Vincent et al. 2012) times smaller. The updated J-factor for Draco (Ackermann et al. 2014; Evans et al. 2016) is furthermore ~ 5 times smaller than what was used by Hooper et al. (2004). This may also apply to Sag, although its morphological structure is more complex due to tidal stripping. Overall, this means that our measurement of the Sag flux does little to constrain the galactic centre signal.

Based on available J-factors (Evans et al. 2016), and assuming in-situ positron annihilation and negligible positronium formation, the strongest constraint we obtain on a DM origin comes from Ursa Major II, due to its large J-factor. At 2σ confidence level, we derive

$$\langle \sigma v \rangle < 5.6 \times 10^{-28} \left(\frac{m_{DM}}{\text{MeV}} \right)^2 \text{ cm}^3 \text{ s}^{-1}. \quad (4)$$

This constraint is still two order of magnitude above the cross section required to explain the entire MW bulge signal, and could be weakened even further if the density of interstellar gas is too low for e^+ s to efficiently find partners to annihilate with.

4.3. Reticulum II

The ultra-faint dwarf galaxy Ret II (Koposov et al. 2015a; Simon et al. 2015) is found with a significance of 3.1σ . This is tantalising evidence for a bright source of positrons in Ret II, and among the other DSGs, Ret II might be special from the perspective of two different, maybe unrelated, measurements:

Ji et al. (2016) measured strong enhancements of neutron-capture elements in stars of Ret II, and interpret this as the result of nucleosynthesis of heavy elements from a single enrichment event only, which then would have to be a neutron star merger. The same enrichment event could be a positron source, e.g. through evolving into an accreting black hole system, or else

the existence of such neutron star binary also makes plausible the existence of a microquasar, producing e^+ s in flaring states. On the other hand, there are suggestions for a star formation connection: Geringer-Sameth et al. (2015) reported a 2-10 GeV γ -rays with Fermi/LAT at 2.3 to 3.7σ significance, and such γ -rays have been associated with star formation through cosmic-ray/gas interactions (Abdo et al. 2010; Ackermann et al. 2012, 2016). The effects of star formation are a non-negligible prerequisite for the 511 keV emission in the MW, as β^+ -unstable radioactive nuclei are produced mainly in massive stars and their supernovae, and definitely contribute to the e^+ -content in our Galaxy (see e.g. Diehl et al. 2006; Prantzos et al. 2011; Churazov et al. 2011; Alexis et al. 2014).

At a distance of 30 kpc, Ret II shows a present-day positron annihilation rate (assuming a positronium fraction of 1.0) of $(3.7 \pm 1.2) \times 10^{43} \text{ e}^+ \text{ s}^{-1}$. This value is at least as high as the one for the entire MW $((3.5 - 6.0) \times 10^{43} \text{ e}^+ \text{ s}^{-1}$, see Paper I), and would support either the neutron star merger hypothesis of Ji et al. (2016) or the star formation picture of Geringer-Sameth et al. (2015). Either case may have produced a huge number of e^+ s whose gradual, ongoing annihilation we now see in the ISM of Ret II.

Although the GeV excess in Ret II may also be attributed to DM particle annihilation, the Fermi/LAT data itself does not favour one or the other annihilation channel, because of the large uncertainty in the DM content (J-factor) of Ret II (Geringer-Sameth et al. 2015). Furthermore, Ret II and the LMC are the only DSGs that show a high-energy excess, disfavoured by a DM explanation of the signal, as otherwise more DSGs should have been detected (Ackermann et al. 2014). Using the J-factors from Evans et al. (2016), a DM-only interpretation of the 511 keV signal from Ret II yields a cross section that would require a galactic bulge signal ~ 100 times larger than observed. Indeed, this would indicate that at most $\sim 1\%$ of Ret II's signal is due to DM annihilation.

5. Conclusion

We reported a search for 511 keV electron-positron annihilation emission from the satellite galaxies of the Milky Way within 500 kpc. Out of 39 tested sources, we find a signal from only one galaxy, Reticulum II, with a significance of 3.1σ . The results for all other satellite galaxies are not in contradiction although not entirely consistent with statistical fluctuations of background. A combined (stacking) analysis of the satellite galaxies, assuming they share a common dark matter mass scale (Strigari et al. 2008a), also does not yield a positive signal, and we provide a 2σ upper limit on the dark-matter related 511 keV line flux of $1.4 \times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$. For a subset of galaxies with available masses and J-factors, we estimate a mass- and distance-weighted upper limit on the flux of $2.3 \times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$ (see included galaxies in Tab. 1). Even when we tentatively accept all marginal signals, the measured fluxes do not scale with the distances to the satellite galaxies. Furthermore, the closest satellite galaxy in our sample, Canis Major, does not show any signal ($< 4.1 \times 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$ at 2σ), though it might be influenced by extended emission from the galactic plane.

We have established a firm upper limit on the 511 keV emission from a dark matter origin, though more sensitivity will be required to test the dark matter hypothesis as the origin of the signal. The case of Reticulum II and the 511 keV signal from this galaxy cannot entirely be attributed to dark matter; other origins related to star formation or a single neutron star merger (Geringer-Sameth et al. 2015; Ji et al. 2016), are thus more plausible.

sible. Furthermore, we have used the constraints for the galactic centre 511 keV signal to show that the Reticulum II signal cannot be from dark matter alone. Understanding the signal of this dwarf galaxy may give clues about the true origin of the Milky Way bulge signal.

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Table 1: List of Milky Way satellites tested for 511 keV emission, ordered by distance. The measured line flux F_{511} is given in 10^{-5} ph cm $^{-2}$ s $^{-1}$. M_{Dyn} are the dynamical masses of the satellite in units of $10^6 M_{\odot}$, M_V their absolute visual magnitude, and d the distance in kpc. The significance of a possible line detection is given in units of sigma. 2σ or above detections are marked boldface. If a line is not present at all, a 2σ upper limit on the flux is given. The positions of the assumed centres of the satellites are given in galactic longitude l and latitude b in units of degrees. The effective exposure time at the position of the sources T_{Exp} is given in Ms. M_{Dyn} , M_V , d , l , and b are taken from the literature (references, last column). The distances have been chosen as the given mean value from the NASA/IPAC Extragalactic Database (NED), if available.

Name	d	F_{511}	M_{Dyn}	M_V	σ	l	b	T_{Exp}	Ref.
Canis Major ^b	9	< 4.1	> 49	-14.4	–	239.99	-8.00	0.62	(1),(16),(17)
Segue 1 ^b	23	< 12.4	0.26	-1.5	–	220.48	50.43	0.16	(1),(12),(60),(61),(62),(63)
Sagittarius Dwarf	28	2.2(1.0)	190	-13.4	2.3	5.57	-14.17	7.00	(1),(44),(45),(46)
Reticulum II^c	30	17.0(5.4)	0.24	-2.7	3.1	266.30	-49.73	0.55	(22),(23),(27),(42),(43)
Ursa Major II ^c	34	4.1(2.3)	3.9	-4.2	1.9	152.46	37.44	1.67	(1),(57),(58),(59)
Segue 2 ^c	35	< 14.4	0.23	-2.5	–	149.43	-38.14	0.20	(1),(48)
Willman 1 ^c	42	7.3(7.1)	0.39	-2.7	1.0	158.58	56.78	0.45	(1),(62),(64),(65)
Coma Berenices ^c	44	1.6(1.7)	0.94	-4.1	1.0	241.89	83.61	2.93	(1),(6),(12),(18)
Boötes III	48	< 4.4	> 0.017	-5.8	–	35.41	75.35	1.93	(1),(8),(9),(10)
Boötes II ^a	49	< 5.8	3.3	-2.7	–	353.69	68.87	1.92	(1),(5),(6),(7)
Large Magellanic Cloud	50	< 3.6	> 1500	-18.1	–	280.47	-32.89	4.22	(1),(37),(38)
Tucana II ^c	57	3.8(8.4)	N/A	-3.8	0.5	328.08	-52.32	0.22	(22),(23)
Small Magellanic Cloud	61	0.6(2.8)	1400	-16.8	0.2	302.80	-44.30	1.38	(1),(37),(52),(53)
Boötes I^{a,c}	62	8.5(2.9)	0.81	-6.3	3.0	358.08	69.62	1.85	(1),(2),(3),(4)
Ursa Minor ^c	73	< 5.8	9.5	-8.8	–	104.97	44.80	1.30	(1),(29)
Horologium I ^c	79	6.7(4.4)	0.55	-3.4	1.6	271.39	-54.73	0.43	(22),(23),(27)
Draco ^c	82	< 3.8	11	-8.8	–	86.37	34.72	1.57	(1),(19),(20),(21)
Phoenix II	83	< 16.6	N/A	-2.8	–	323.68	-59.75	0.19	(22),(23)
Sculptor ^c	83	< 11.6	14	-11.1	–	287.54	-83.16	0.22	(1),(47)
Sextans ^c	85	6.5(5.3)	10.6	-9.3	1.2	243.50	42.27	0.12	(1),(49),(50),(51)
Eridanus III	87	7.3(5.1)	N/A	-2.0	1.5	274.95	-59.60	0.38	(22),(23)
Indus I	100	6.2(3.9)	N/A	-3.5	1.6	347.15	-42.07	0.26	(23),(23)
Ursa Major I ^c	101	< 9.2	11	-5.5	–	159.43	54.41	0.42	(1),(6),(54),(55),(56)
Carina ^c	103	0.6(3.6)	6.3	-9.1	0.2	260.11	-22.22	0.66	(1),(14),(15)
Pictoris I	114	< 7.4	N/A	-3.1	–	257.29	-40.64	0.46	(22),(23)
Grus I^c	120	20.8(9.1)	N/A	-3.4	2.3	338.68	-58.25	0.12	(22),(23)
Hercules	136	9.7(5.5)	2.6	-6.6	1.8	28.73	36.87	0.31	(1),(6),(12),(26)
Fornax ^c	139	16.9(9.6)	56	-13.4	1.8	237.10	-65.65	0.11	(1),(24),(25)
Canes Venatici II^c	153	5.0(2.2)	0.91	-4.9	2.3	113.58	82.70	2.44	(1),(6),(12),(13)
Leo IV ^c	155	< 5.4	1.3	-5.8	–	265.44	56.51	1.84	(1),(6),(12),(13)
Pisces II ^c	182	2.9(4.3)	> 0.0086	-5.0	0.7	79.21	-47.11	0.79	(1),(39),(40),(41)
Leo V ^c	186	3.7(3.3)	1.1	-5.2	1.1	261.86	58.54	1.96	(1),(35),(36)
Canes Venatici I ^c	216	1.2(2.2)	19	-8.6	0.6	74.31	79.82	1.84	(1),(6),(11)
Leo II ^c	218	5.0(5.5)	4.6	-9.8	0.9	220.17	67.23	0.35	(1),(31),(32)
Leo I^c	246	15.8(7.4)	12	-12	2.2	225.99	49.11	0.12	(1),(28),(29),(30)
Eridanus II	380	< 21.6	N/A	-6.6	–	249.78	-51.65	0.10	(22),(23)
Leo T ^c	412	6.1(6.5)	3.9	-8.0	1.0	214.85	43.66	0.19	(1),(33),(34)
Phoenix I	418	4.3(5.7)	9.7	-9.9	0.8	272.16	-68.95	0.36	(1),(66),(67),(68),(69)
NGC 6822	498	1.4(1.6)	3500	-15.2	0.9	25.34	-18.40	2.25	(1),(29),(69),(70),(71),(72)

Notes. (1) (McConnachie 2012), (2) (Belokurov et al. 2006), (3) (Fellhauer et al. 2008), (4) (Dall’Ora et al. 2006), (5) (Walsh et al. 2007), (6) (Grcevich & Putman 2009), (7) (Walsh et al. 2008), (8) (Grillmair 2009), (9) (Carlin et al. 2009), (10) (Correnti et al. 2009), (11) (Zucker et al. 2006), (12) (Belokurov et al. 2007), (13) (Okamoto et al. 2012), (14) (Kraan-Korteweg & Tammann 1979), (15) (Mateo et al. 1998), (16) (Martin et al. 2004), (17) (Martin et al. 2005), (18) (Musella et al. 2009), (19) (Cotton et al. 1999), (20) (Falco et al. 1999), (21) (Tyler 2002), (22) (Koposov et al. 2015a), (23) (The DES Collaboration et al. 2015), (24) (Piatek et al. 2007), (25) (Poretti et al. 2008), (26) (Musella et al. 2012), (27) (Koposov et al. 2015b), (28) (Whiting et al. 2007), (29) (Young 2000), (30) (Caputo et al. 1999), (31) (Coleman et al. 2007), (32) (Gullieuszik et al. 2008), (33) (Irwin et al. 2007), (34) (Clementini et al. 2012), (35) (Belokurov et al. 2008), (36) (de Jong et al. 2010), (37) (Richter et al. 1987), (38) (Feast & Walker 1987), (39) (Belokurov et al. 2010), (40) (Kirby et al. 2015), (41) (Sand et al. 2012), (42) (Simon et al. 2015), (43) (Walker et al. 2015), (44) (Majewski et al. 2003), (45) (Ibata et al. 1994), (46) (Monaco et al. 2004), (47) (Queloz et al. 1995), (48) (Belokurov et al. 2009), (49) (Irwin et al. 1990), (50) (Battaglia et al. 2011), (51) (Lee et al. 2003), (52) (Matsunaga et al. 2011), (53) (Bekki & Stanimirović 2009), (54) (Willman et al. 2005b), (55) (Kleyna et al. 2005), (56) (Okamoto et al. 2008), (57) (Peñarrubia et al. 2006), (58) (Fellhauer et al. 2007), (59) (Dall’Ora et al. 2012), (60) (Norris et al. 2010), (61) (de Jong et al. 2008), (62) (Martin et al. 2008), (63) (Simon et al. 2011), (64) (Willman et al. 2005a), (65) (Willman et al. 2011), (66) (Cote et al. 1997), (67) (Zaggia et al. 2011), (68) (Gallart et al. 2001), (69) (Mateo 1998), (70) (Koribalski et al. 2004), (71) (Rogstad et al. 1967), (72) (Veljanoski et al. 2015)^(a) The values for Boo I may be over- or underestimated due to source confusion with Boo II, being not separated by at least one PSF. Likewise, the value for Boo II may be wrong, too. ^(b) For the stacking analysis, these galaxies have been ignored to validate the flux limit. ^(c) These galaxies have been included in the mass- and distance-weighted stacking analysis due to available dynamical mass and J-factor estimates, see Sect. 3.2.